Managing the Performance of Large, Distributed Storage Systems

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and

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and

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and

Darren Sawyer, NetApp

HEC FSIO 2011

What types of QoS guarantees are useful to HEC application scientists (esp. at exascale)?

- Isolation / virtualization of storage performance
- Guaranteed
  - Checkpoint performance
  - Data capture
  - Performance under varying workloads
  - Performance under concurrent workloads
  - Performance under failure
  - Performance for viz
- What guarantees: throughput & latency

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What is the relationship between QoS infrastructure and other job scheduling infrastructure (e.g., batch schedulers, MapReduce scheduling)?

- Very close relationship
- QoS requirements must inform all system schedulers
- Only possible if
  - Each resource is well understood
  - Requirements are well understood
  - Simplifying principles are found and used

Is the ratio of funded to productized work in QoS lower than in other areas? Yes. If so, why?

- New area—focus has traditionally been on performance, performance, and performance
- Hard *and* requires new ways of thinking
- Crosscutting: storage, real-time, distributed systems, networking, scheduling, ...
- Enabled by excess processor capacity
- Needed by cloud computing and virtualization
- Starting to make it into commercial products
- More on the horizon...

Challenges

- Legacy (intransigent) applications and users
- Scaling—aggregate management
- Crossing the threshold to usability
- Varied resources, applications, workloads
- Interference between I/O streams
- System management tasks

Distributed systems need performance guarantees

- *Many* systems and applications want I/O performance guarantees
  - Multimedia, high-performance simulation, transaction processing, virtual machines, cloud services, service level agreements, real-time data capture, sensor networks, ... system tasks like backup and recovery ... even so-called best-effort applications
- Providing guarantees is difficult
  - Interacting resources, dynamic workloads, interference among workloads, non-commensurable metrics
- Needs
  1. Guaranteed performance
  2. Isolation between workloads
  3. High performance

In a nutshell

- Big distributed systems
  - Serve many users/jobs
  - Process petabytes of data
- Data center design
  - Use rules of thumb
  - Over-provision
  - Isolate

- Ad hoc performance management approaches creates *expensive* and *marginal* solutions
- A better system guarantees each user the performance they need from the CPUs, memory, disks, and network

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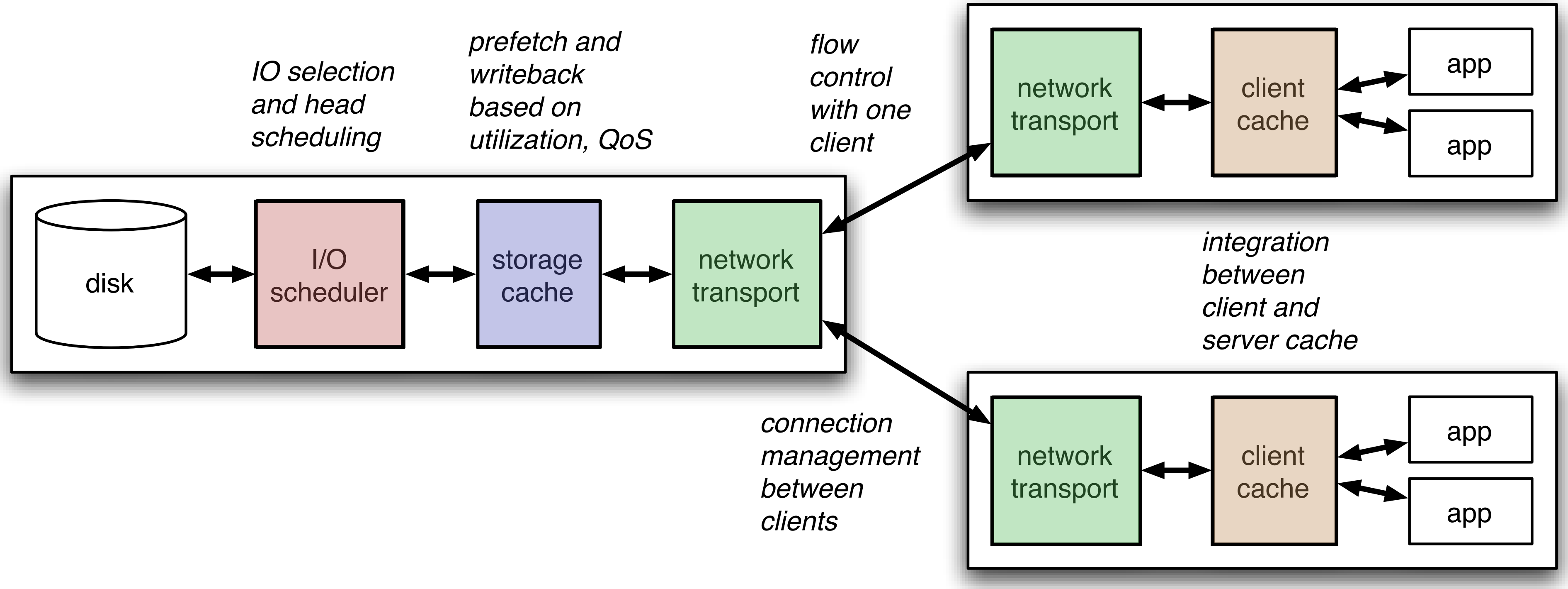
Our approach

1. A uniform model for performance management
2. Apply it to each resource
3. Integrate the solutions

1. Disk I/O
2. Server cache
3. Flow control across network
4. Client cache



Achieving robust guaranteeable resources

- Goal: Unified resource management algorithms capable of providing
  - Good performance
  - Arbitrarily hard or soft performance guarantees with
    - Arbitrary resource allocations
    - Arbitrary timing / granularity
  - Complete isolation between workloads
  - All resources: CPU, disk, network, server cache, client cache

➡Virtual resources indistinguishable from “real” resources with fractional performance

Isolation is key

- CPU
  - 20% of a 3 Ghz CPU should be indistinguishable from a 600 Mhz CPU
  - Running: compiler, editor, audio, video
- Disk
  - 20% of a disk with 100 MB/second bandwidth should be indistinguishable from a disk with 20 MB/second bandwidth
  - Serving: 1 stream, *n* streams, sequential, random

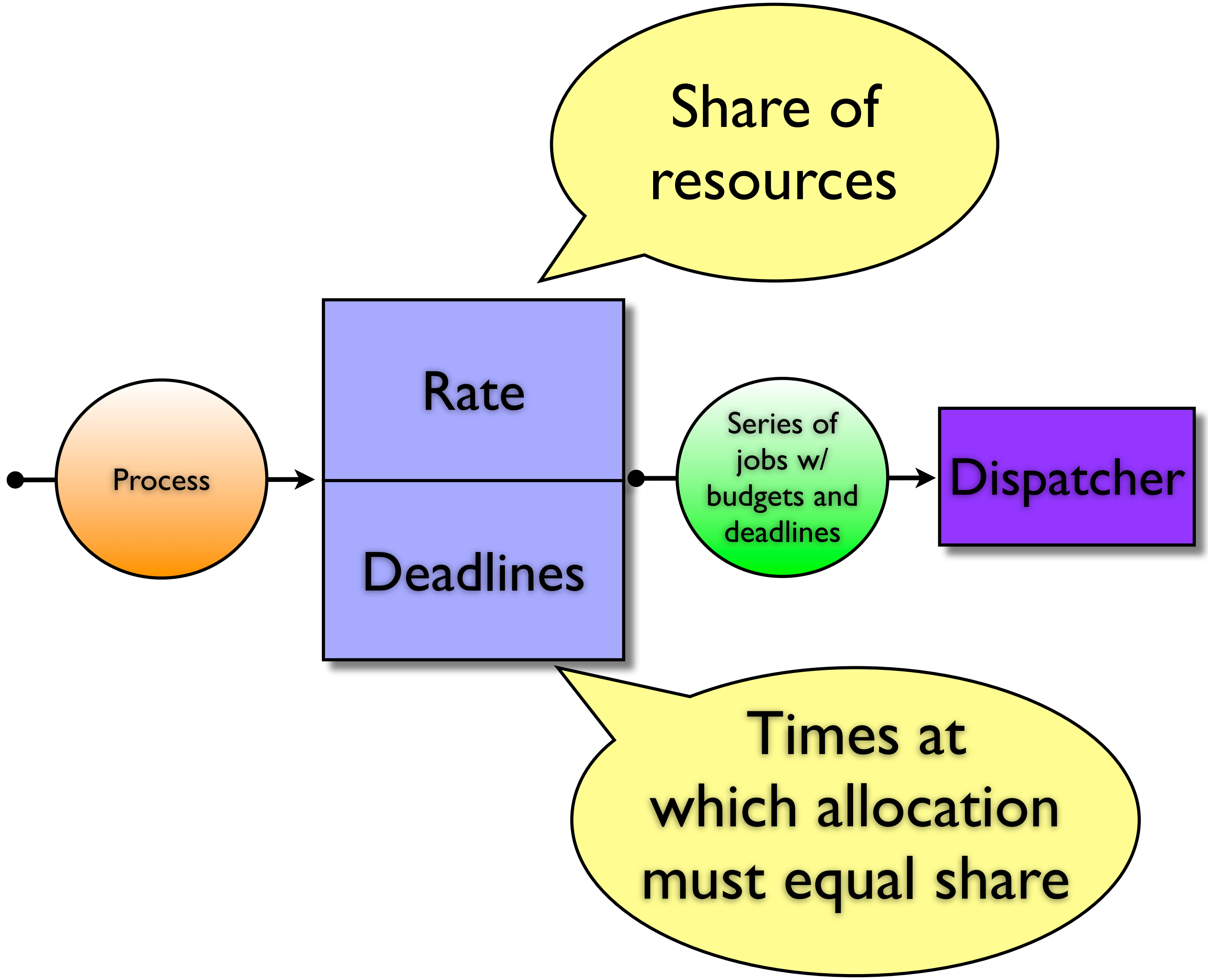
Scott's epistemology of virtualization

- Virtual Machines and LUNs provide good HW virtualization
- Question: Given perfect HW virtualization, *how can a process tell the difference between a virtual resource and a real resource?*
- Answer: By not getting its **share** of the resource **when** it needs it

Observation

- Resource management consists of two distinct decisions
  - Resource Allocation: *How much* resources to allocate?
  - Dispatching: *When* to provide the allocated resources?
- Most resource managers conflate them
  - Best-effort, proportional-share, real-time

The resource allocation/dispatching (RAD) scheduling model



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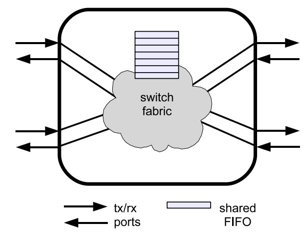
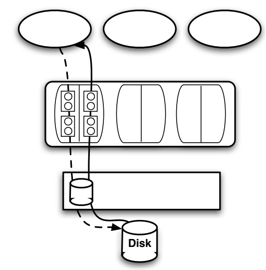
Adapting RAD to disk, network, and buffer cache

- Fahrrad—Guaranteed disk request scheduling
  Anna Povzner

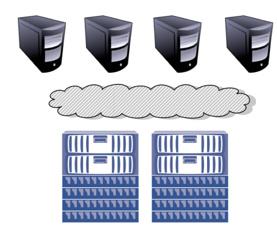
- RADoN—Guaranteeing storage network performance
  Andrew Shewmaker



- Radium—Buffer management for I/O guarantees
  Roberto Pineiro



- Horizon—I/O management for distributed storage systems
  Anna Povzner



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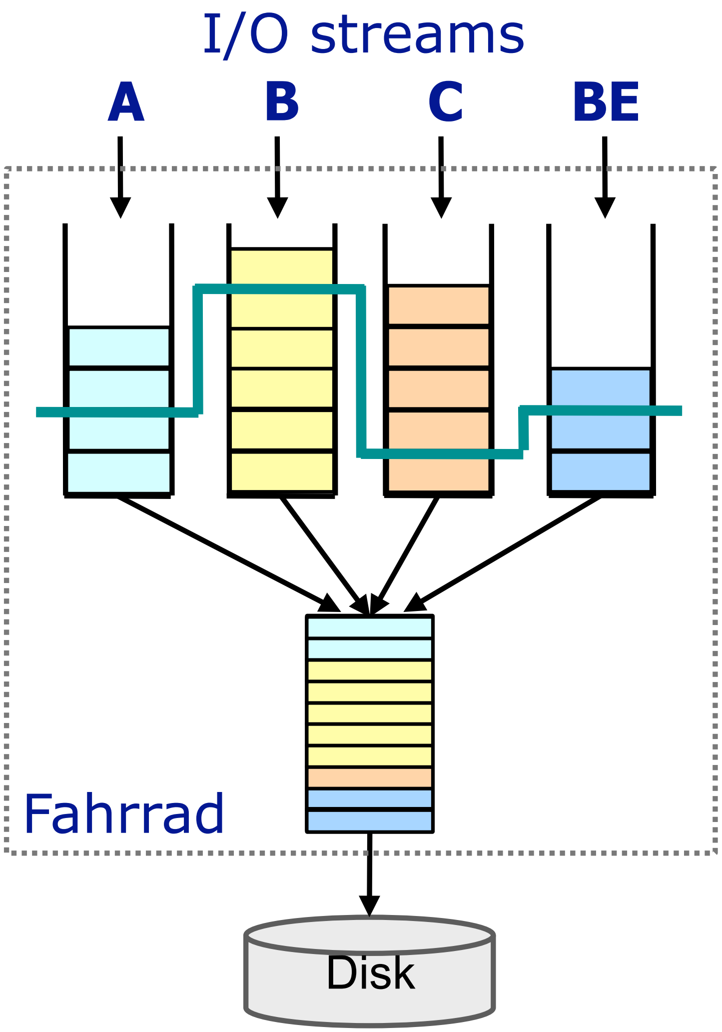
Guaranteed disk request scheduling

- Goals
  - Hard and soft performance guarantees
  - Isolation between I/O streams
  - Good I/O performance
- Challenging because disk I/O is:
  - Stateful
  - Non-deterministic
  - Non-preemptable, and
  - Best- and worst-case times vary by 3–4 orders of magnitude

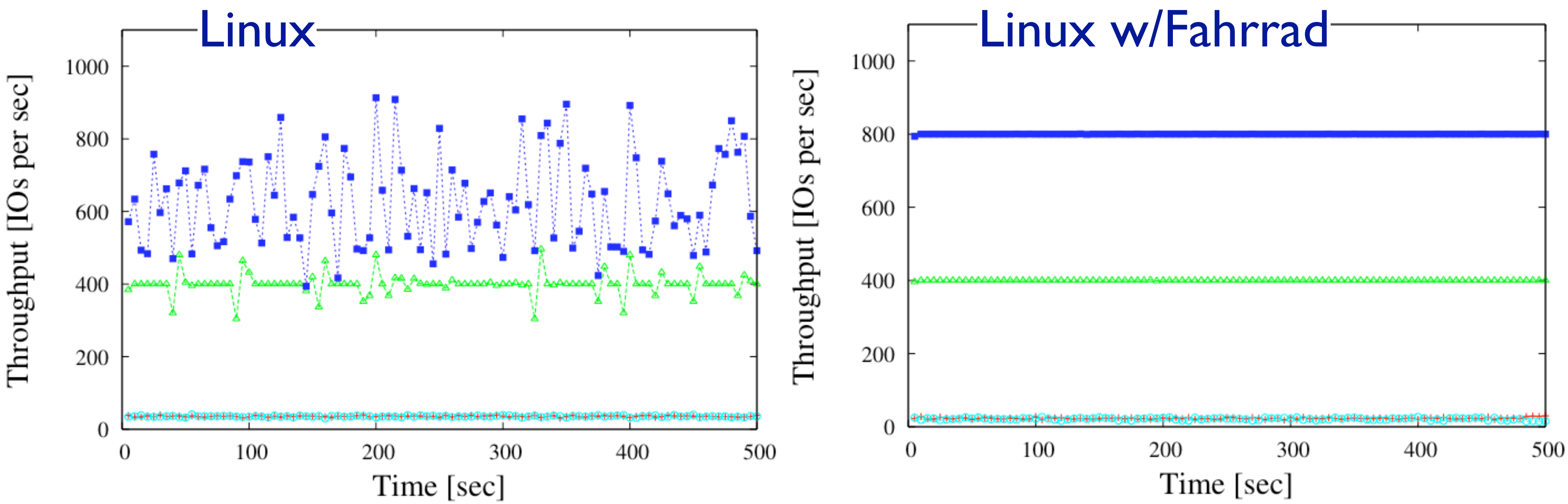
Fahrrad

- Manages disk *time* instead of disk *throughput*
- Adapts RAD/RBED to disk I/O
- Reorders aggressively to provide good performance, without violating guarantees



Anna Povzner, Tim Kaldewey, Scott A. Brandt, Richard Golding, Theodore Wong, and Carlos Maltzahn, "*Efficient Guaranteed Disk Request Scheduling with Fahrrad*", Eurosys 2008.

Fahrrad outperforms Ext2/3



- Workload
  - Media 1: 400 sequential I/Os per second (20%)
  - Media 2: 800 sequential I/Os per second, (40%)
  - Transaction: short bursts of random I/Os at random times (30%)
  - Background: random (10%)
- Result: Better isolation AND better throughput

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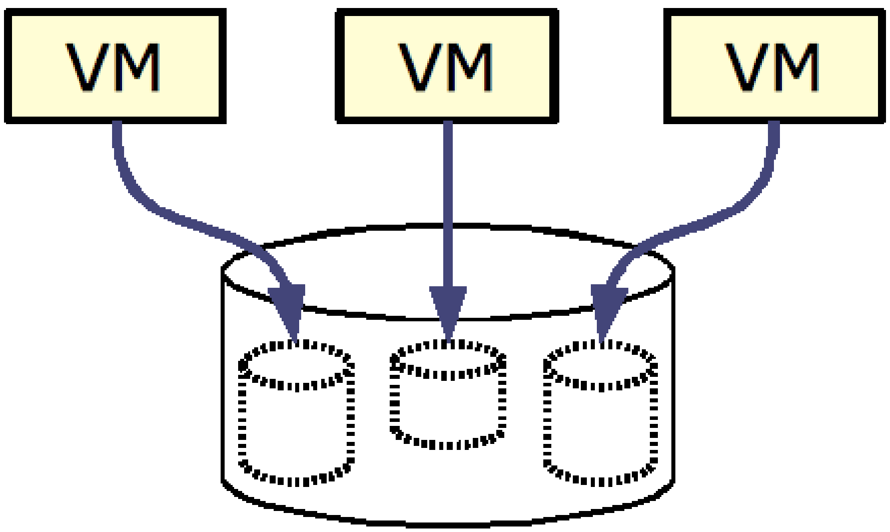
Fahrrad virtual disks

- Provide workload-independent performance guarantees
- Isolate from other workloads concurrently accessing the device



- LUNs virtualize *storage capacity*
- Fahrrad virtualizes *storage performance*

Fahrrad virtual disks

- Implemented with the Fahrrad real-time I/O scheduler
- Guarantee reserved and isolated share of the time on storage device
  - Hard guarantees on performance isolation
  - Virtual disk throughput same as equivalent standalone throughput
- Amount of data transferred:
  - $\forall i,\ D_i(\underbrace{x\%}_{\text{Share of disk}}, \underbrace{t}_{\text{Time}}) = D_i(\underbrace{100\%}_{\text{Share of disk}}, \underbrace{x\% \cdot t}_{\text{Time}})$

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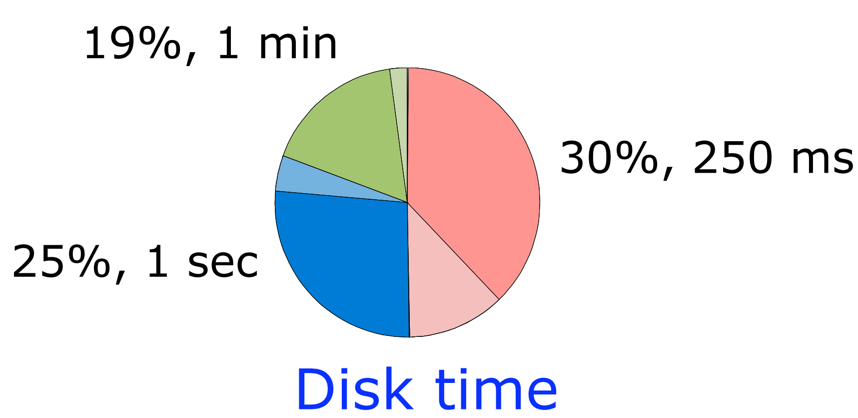
Ensuring isolation

- Virtual disk reservation: *disk share (utilization)* and *time granularity (period)*
  - Account for all extra (inter-stream) seeks
  - Reserve overhead utilization to do them
  - Charge each I/O stream for all of the time it uses, including inter- and intra-stream seeks
  - Reservation = Disk Share + Overhead utilization



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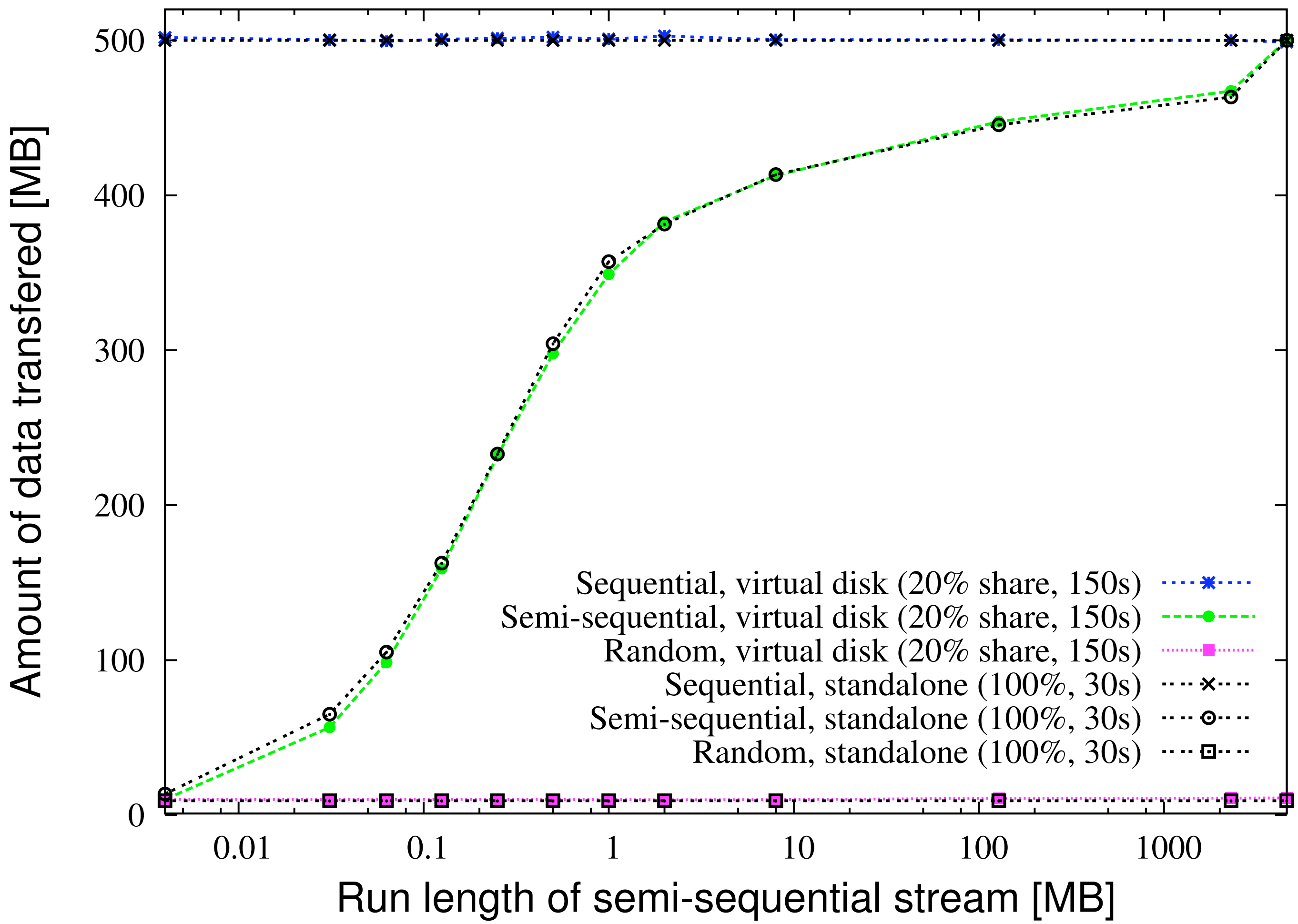
Guaranteeing throughput

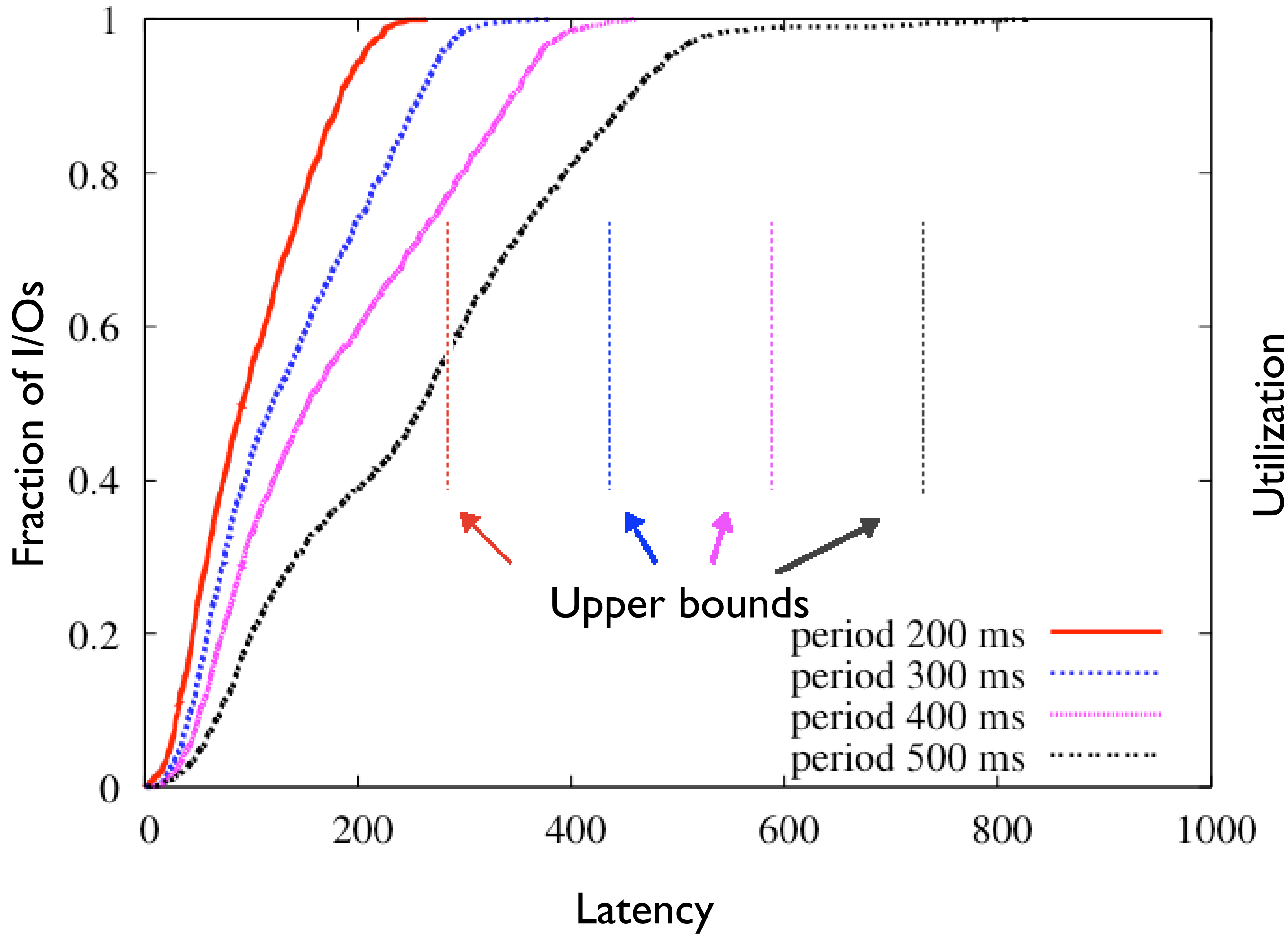
- Throughput is fully determined by reservation & workload
- Virtual disk are completely isolated from each other



Each virtual disk reserves 20% with 1 second granularity

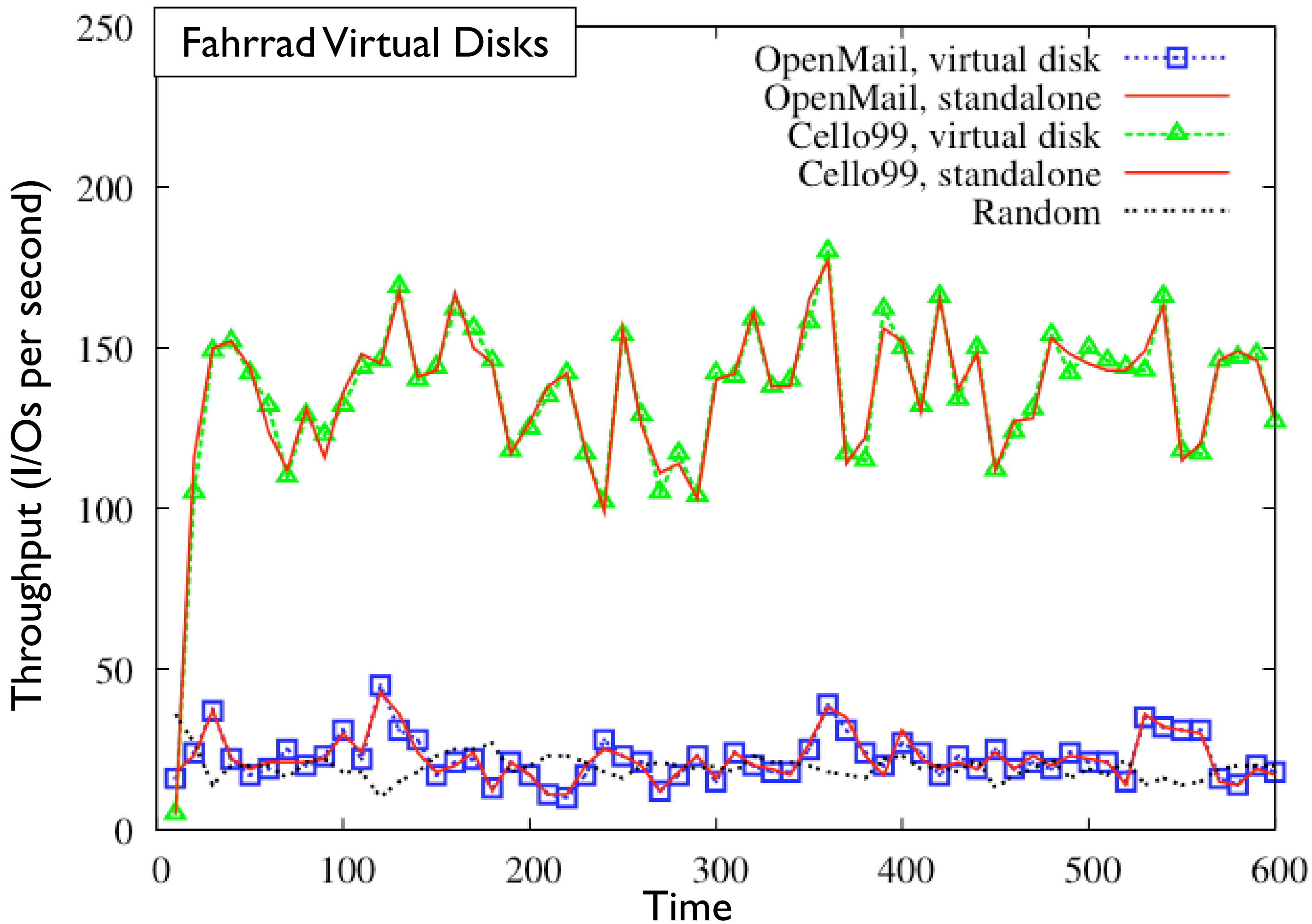
Guaranteeing latency

- Latency is bounded by deadlines

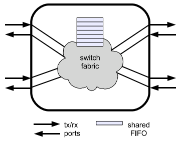


Fahrrad virtual disks work

- Fahrrad Virtual Disks provide Cello99 and OpenMail performance very close to standalone
- Cello99 and OpenMail virtual disks share the system with random background stream.

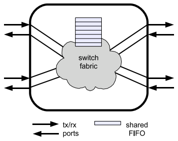


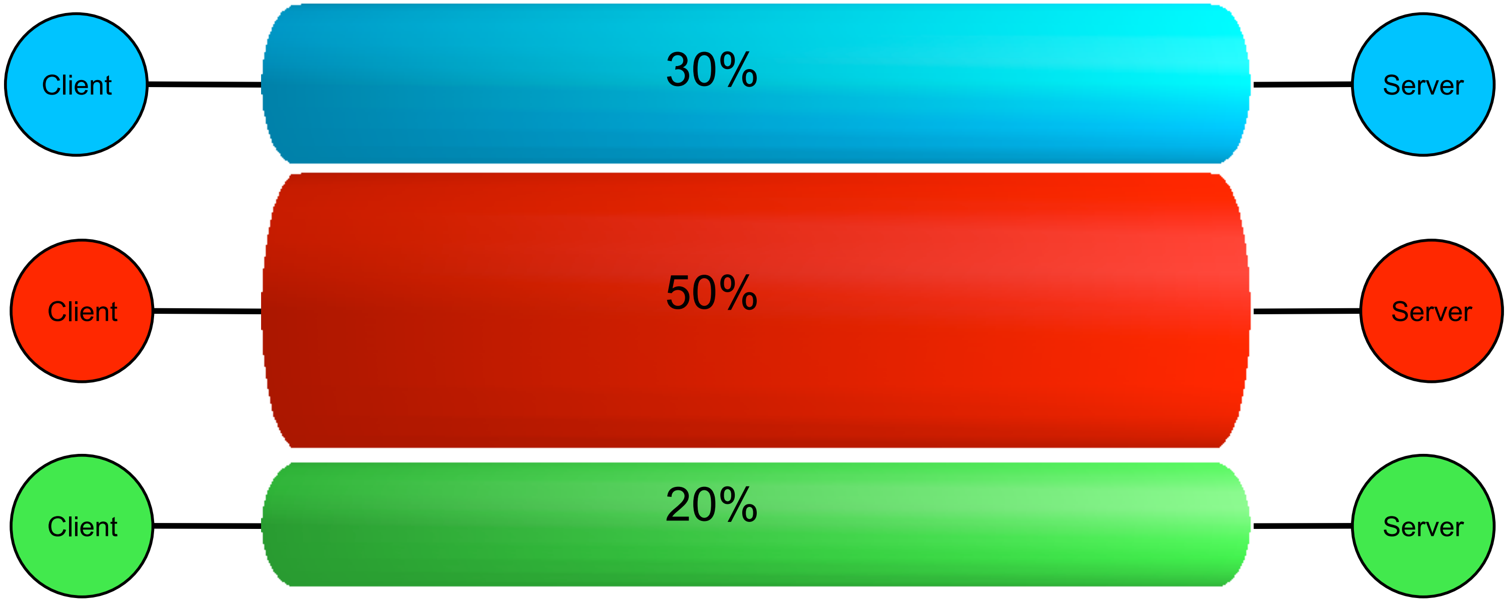
Guaranteeing storage network performance



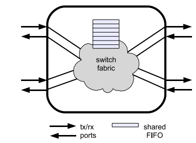
- Goals
  - Hard and soft performance guarantees
  - Isolation between I/O streams
  - Good I/O performance
- Challenging because network I/O is:
  - Distributed
  - Non-deterministic (due to collisions or switch queue overflows)
  - Non-preemptable
- Assumption: closed network

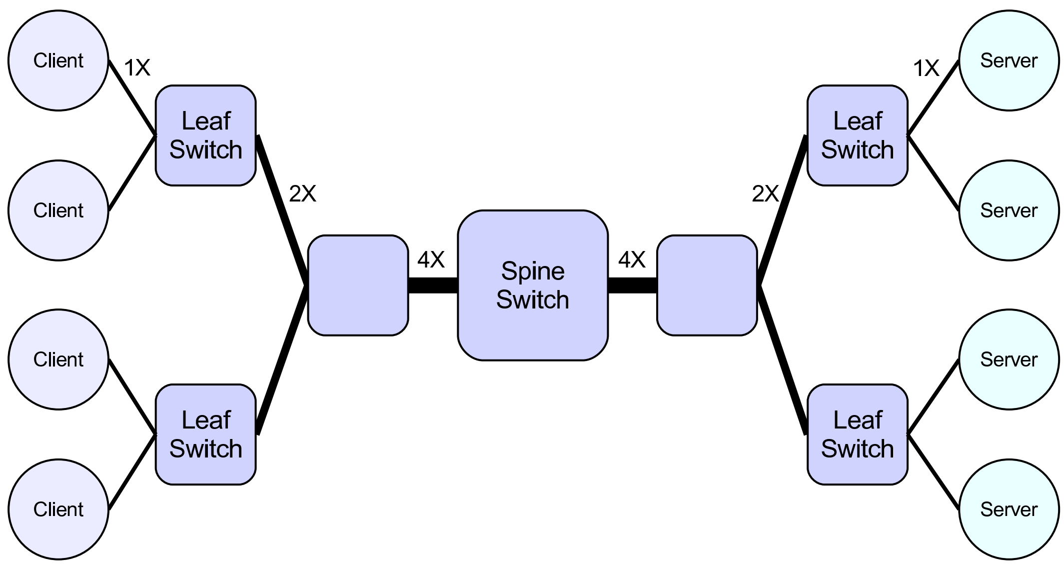
What we want

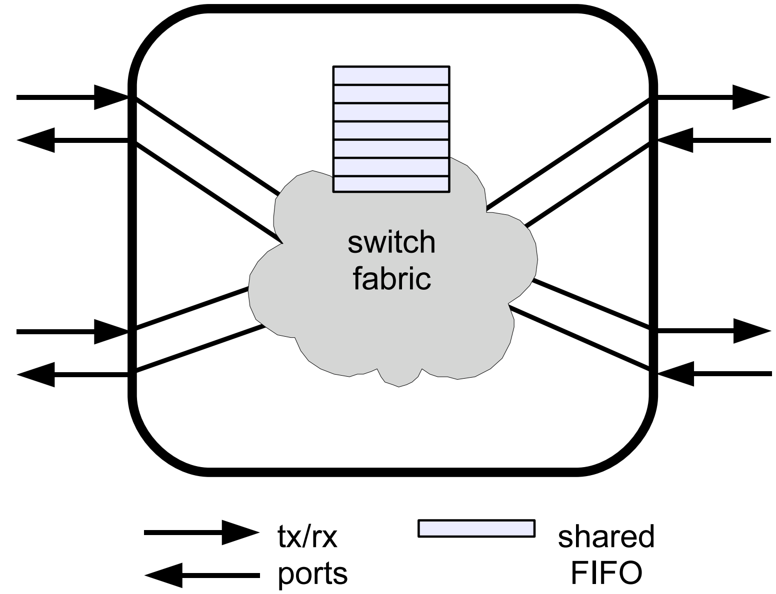

switch
fabric
tx/rx
ports
shared
FIFO


Client
30%
Server
Client
50%
Server
Client
20%
Server

What we have



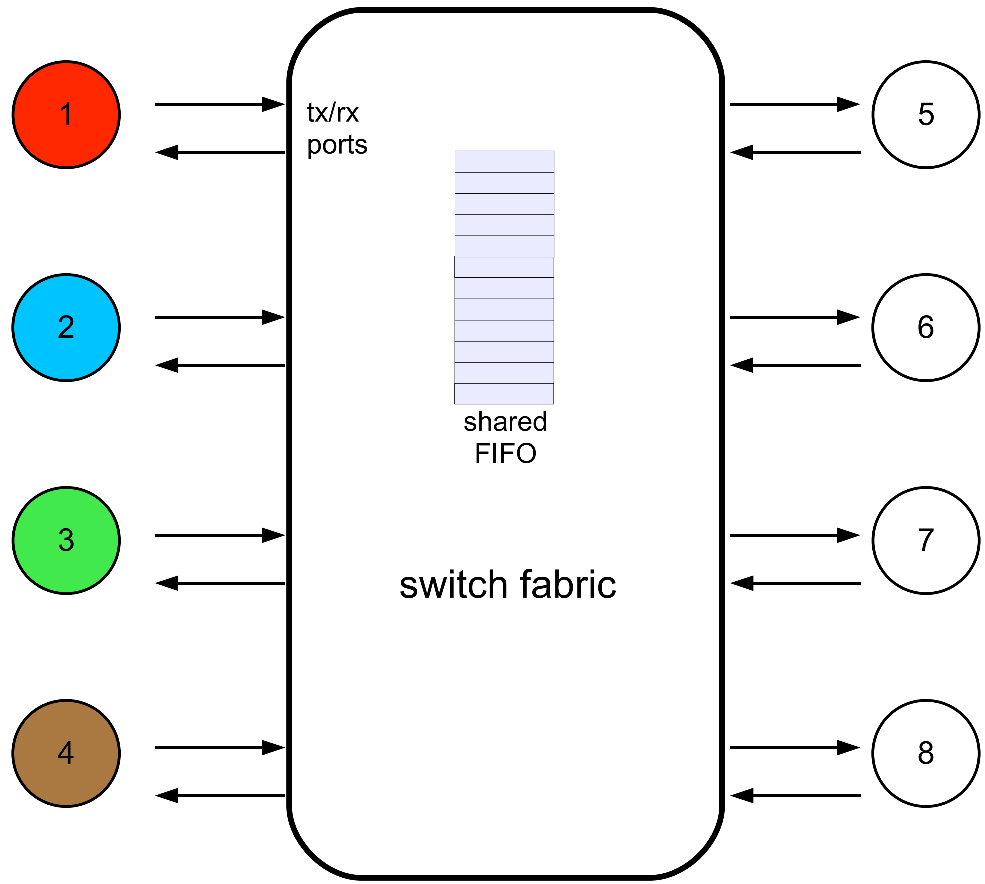




- Switched fat tree w/full bisection bandwidth
- Issue 1: Capacity of shared links
- Issue 2: Switch queue contention

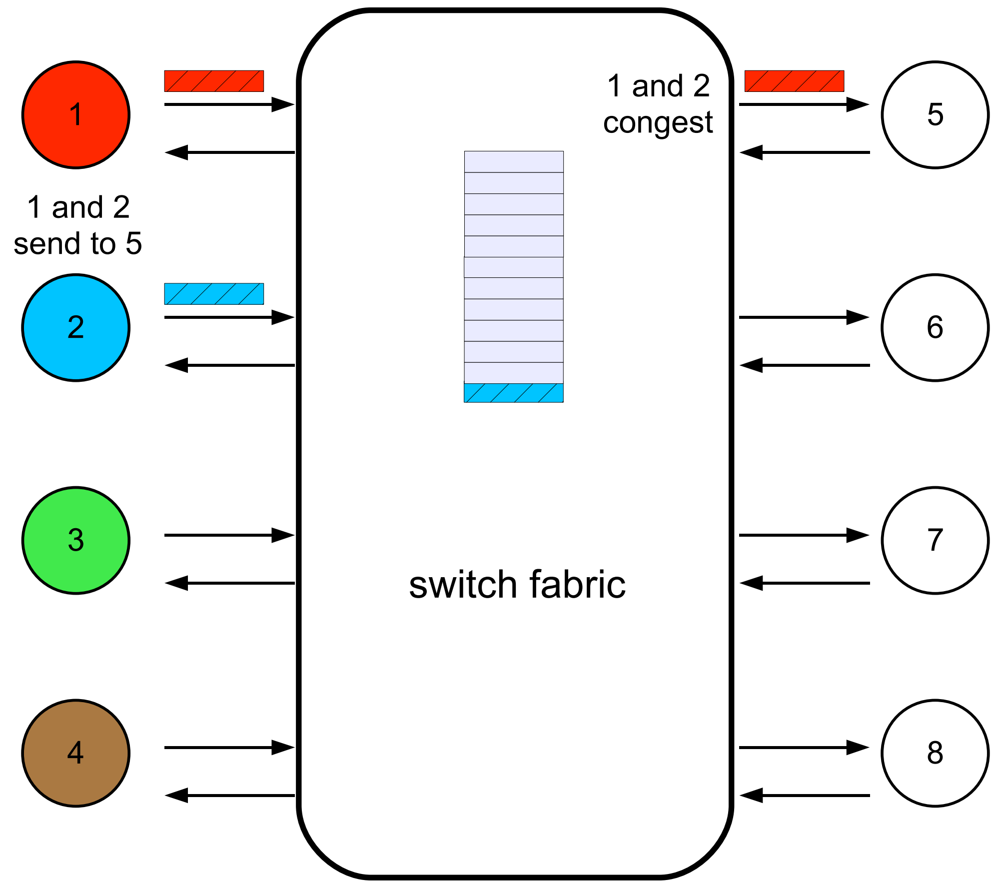
Congestion in a simple switch model

- Each transmit port on the switch is a collision domain



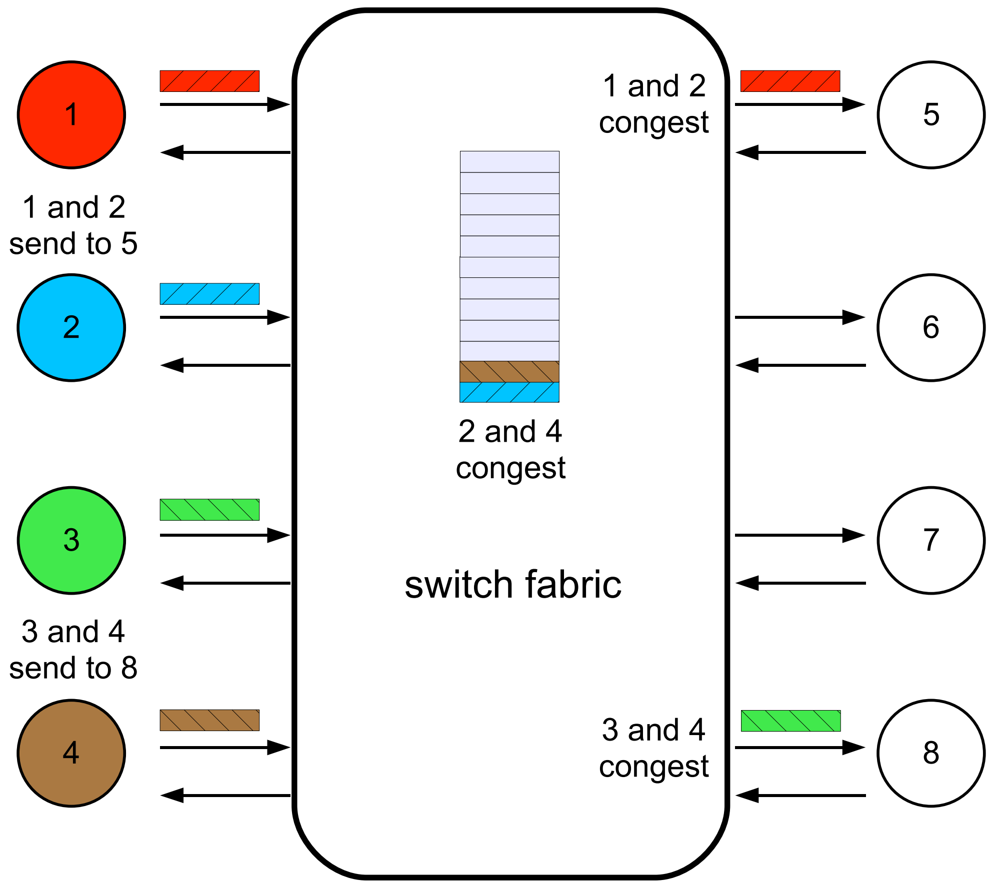
Congestion in a simple switch model

- One of the packets arriving at the same switch transmit port is delayed on the queue



Congestion in a simple switch model

- Delayed packets from unrelated streams affect each other on the queue

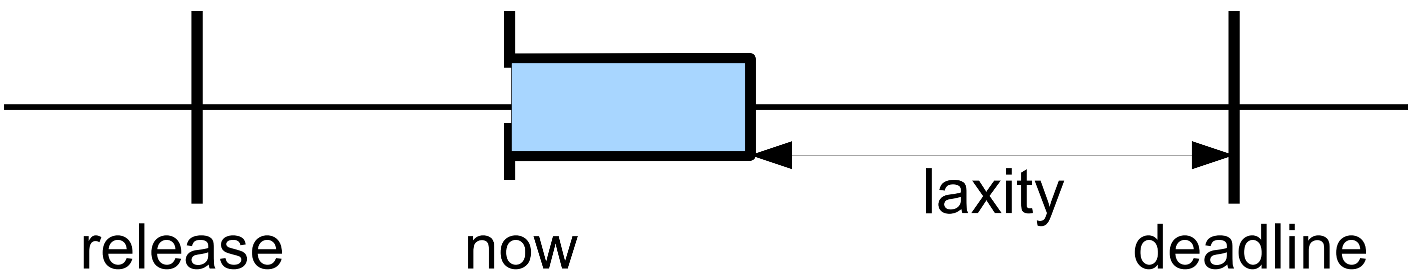


RADoN

- Each reservation has a *network share* (*utilization*) and a *time granularity (period)*

- Flow control: throttle senders
  - Execution time (per period) e = utilization / period
  - Budget in packets m = e / packets_per_second

- Congestion control: avoid switch contention by adjusting wait time between packets
  - Percent budget %budget = (1 - %laxity) = e/(d-t)
  - Packet wait time $w = w_{min}$ / %budget
  - Size change $w\Delta = -|w_i - w_{min}|/2$
  - New wait time $w_{i+1} = \min(w_{max}, \max(w_{min}, w\Delta))$



Tim Kaldewey, Andrew Shewmaker, Carlos Maltzahn, Theodore Wong, and Scott Brandt, "*RADoN: QoS in Storage Networks*", WIP Session of FAST 2008.

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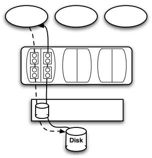
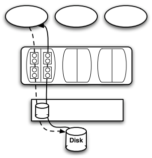
Buffer management for I/O guarantees



- Goals
  - Hard and soft performance guarantees
  - Isolation between I/O streams
  - Improved I/O performance
- Challenging because:
  - Buffer is space-shared rather than time-shared
    - Space limits time guarantees
  - Best- and worst-case are opposite of disk
  - Buffering affects performance in non-obvious ways

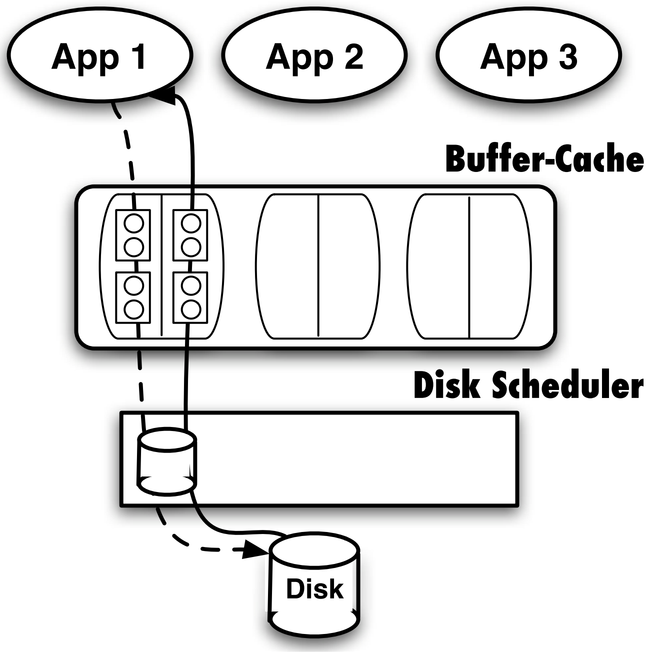
Buffering roles in storage servers



- Decoupling
  - Allows sender and receiver to operate asynchronously
- Speed matching
  - Allows slower and faster devices to communicate
- Traffic shaping
  - Shapes traffic to optimize performance of interfacing devices

Radium

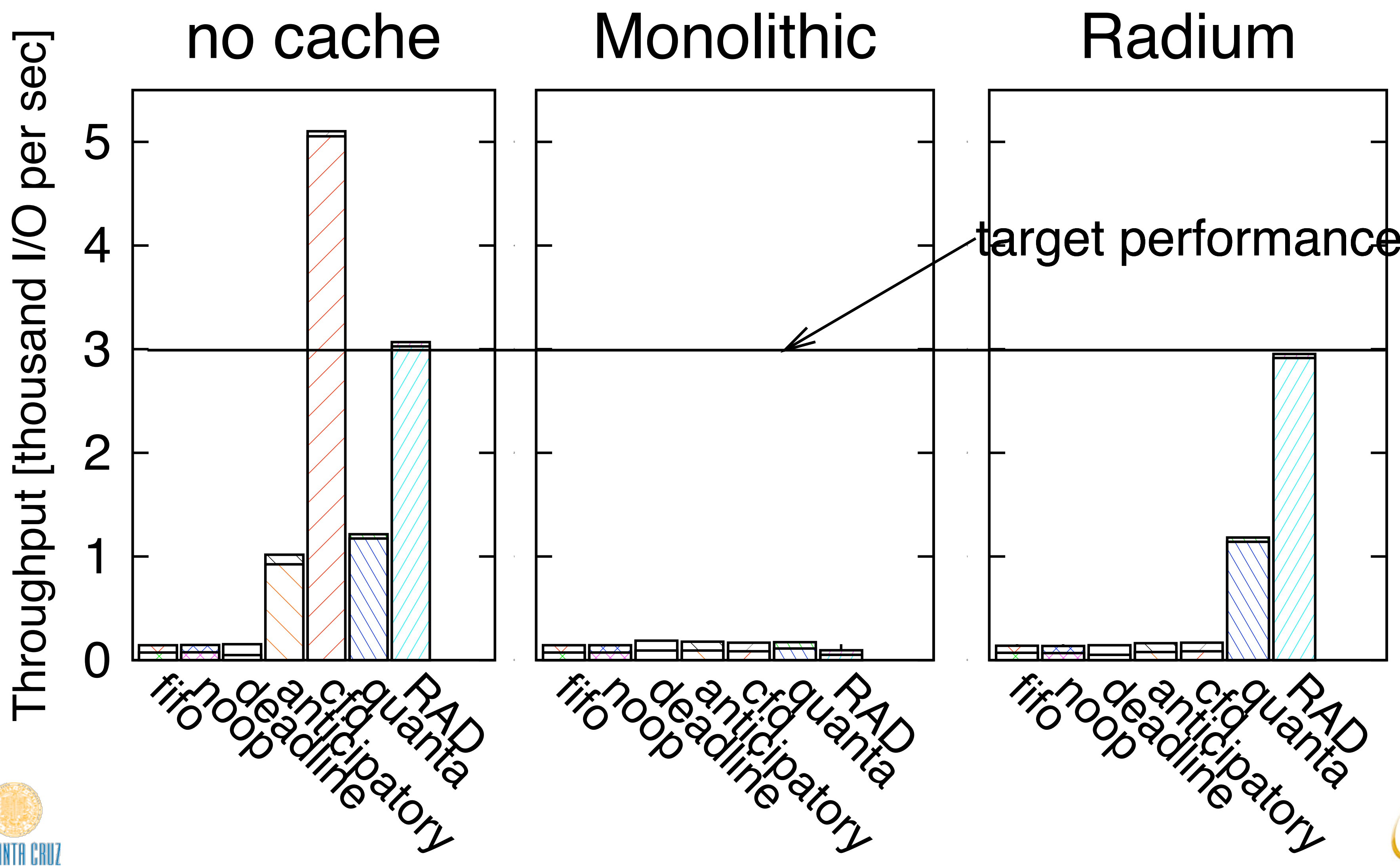
- I/O into and out of buffer have *rates* and *time granularities (periods)*
- Partition buffer space based on I/O characteristics and performance requirements
- Cache policies enhance performance within constraints determined by I/O requirements
  - Use slack to prefetch reads and delay writes



Roberto Pineiro, Kleoni Ioannidou, Carlos Maltzahn, and Scott Brandt, "RAD-FLOWS: Buffering for Predictable Communication," RTAS 2011

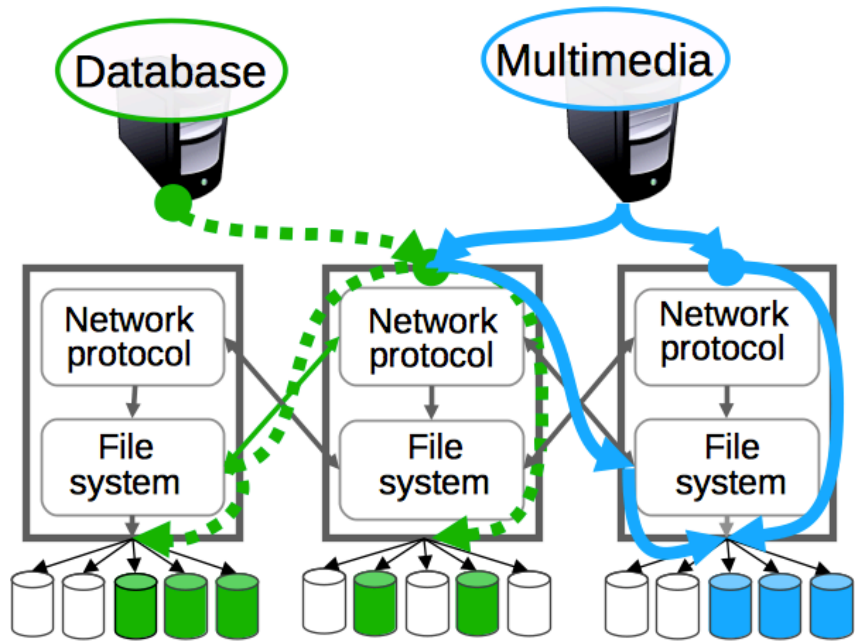
Managing combined workloads

Combined throughput of rand.(top) and seq.(bottom) workloads



Horizon

- Big storage systems are shared, have many disks, and application workloads compete and interfere
- Real distributed systems have
  - Different data layouts
  - Multiple data entry points
  - Different data paths
- Horizon goals
  - Meet performance targets
  - Fully utilize system resources
  - Not rely on reservations
  - Decentralized solution



Anna Povzner, Darren Sawyer, Scott A. Brandt, "Horizon: Efficient Deadline-Driven Disk I/O Management for Distributed Storage Systems," HPDC 2010. **Best Paper**

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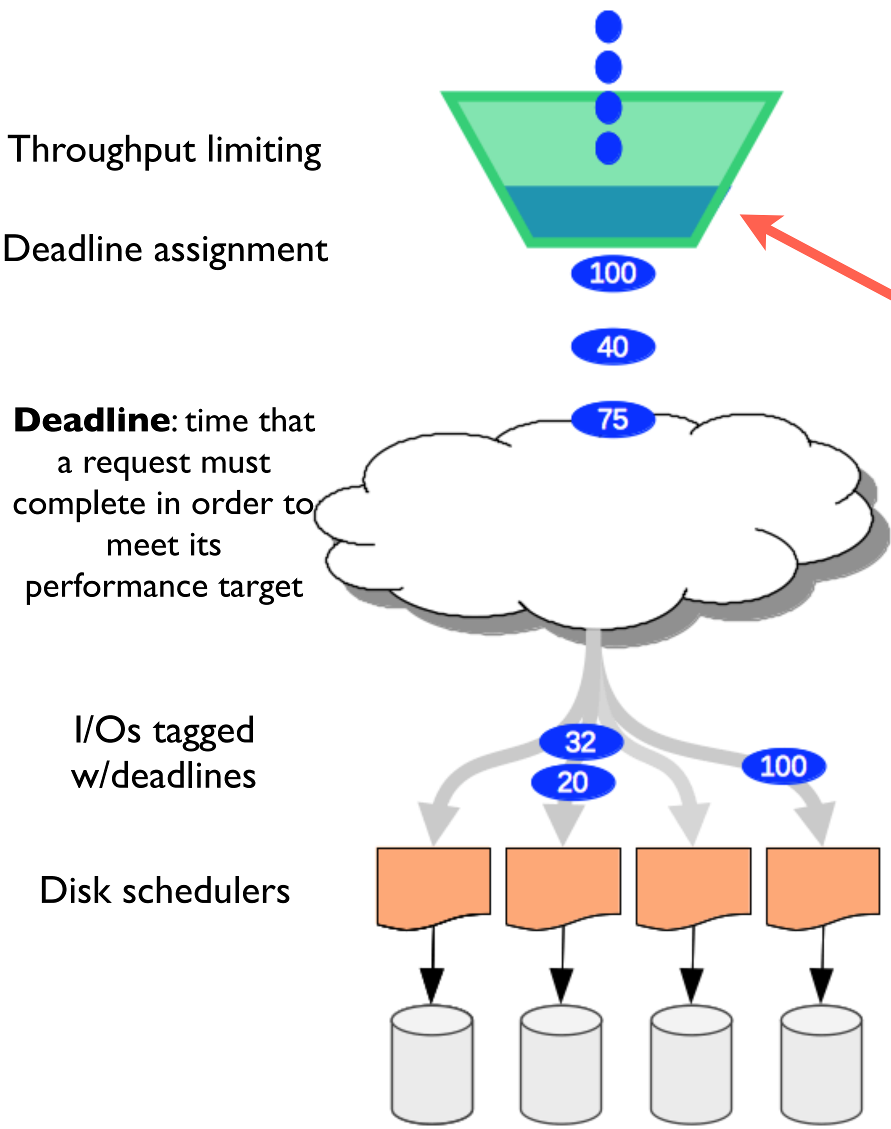
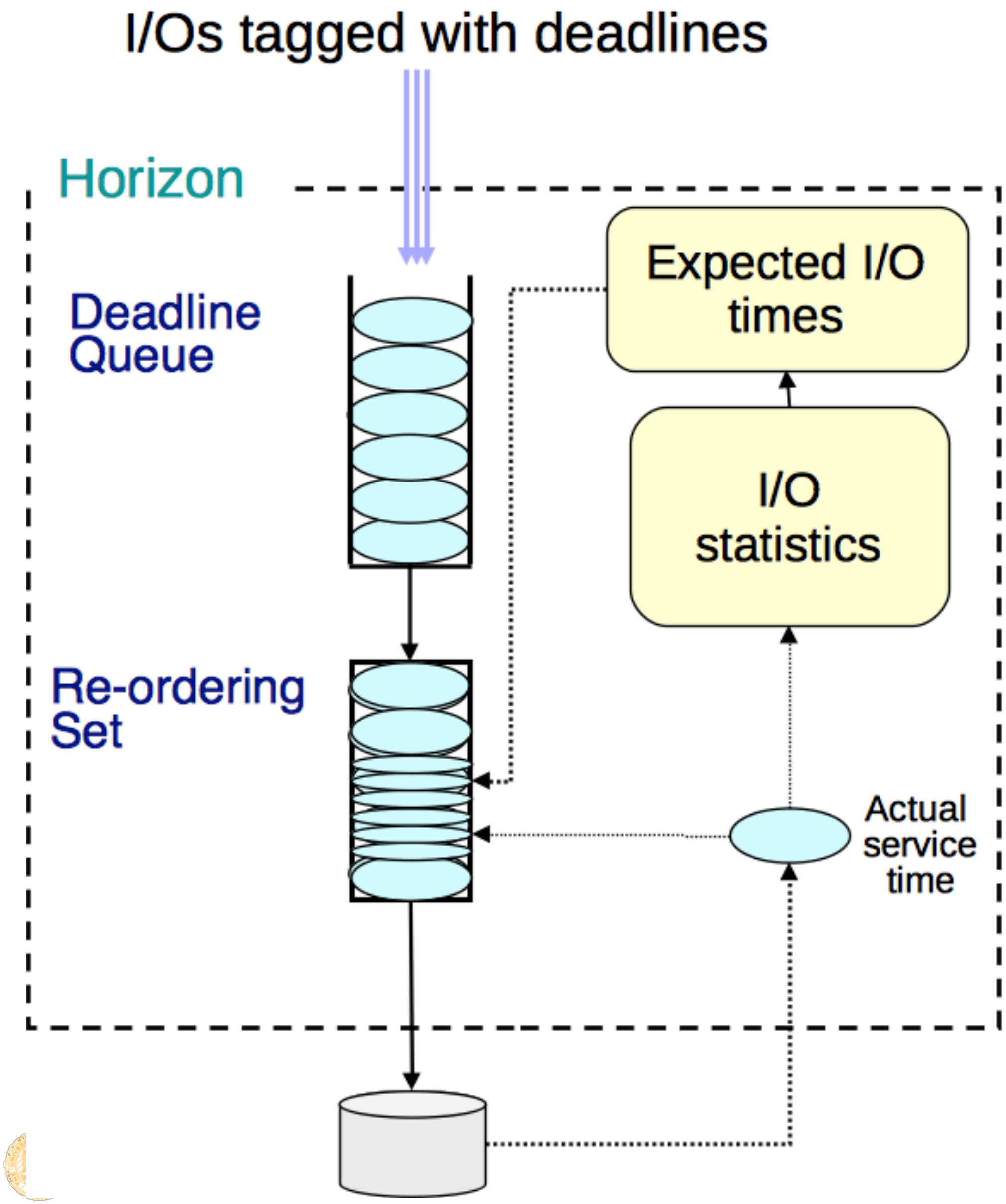
Multi-layered approach



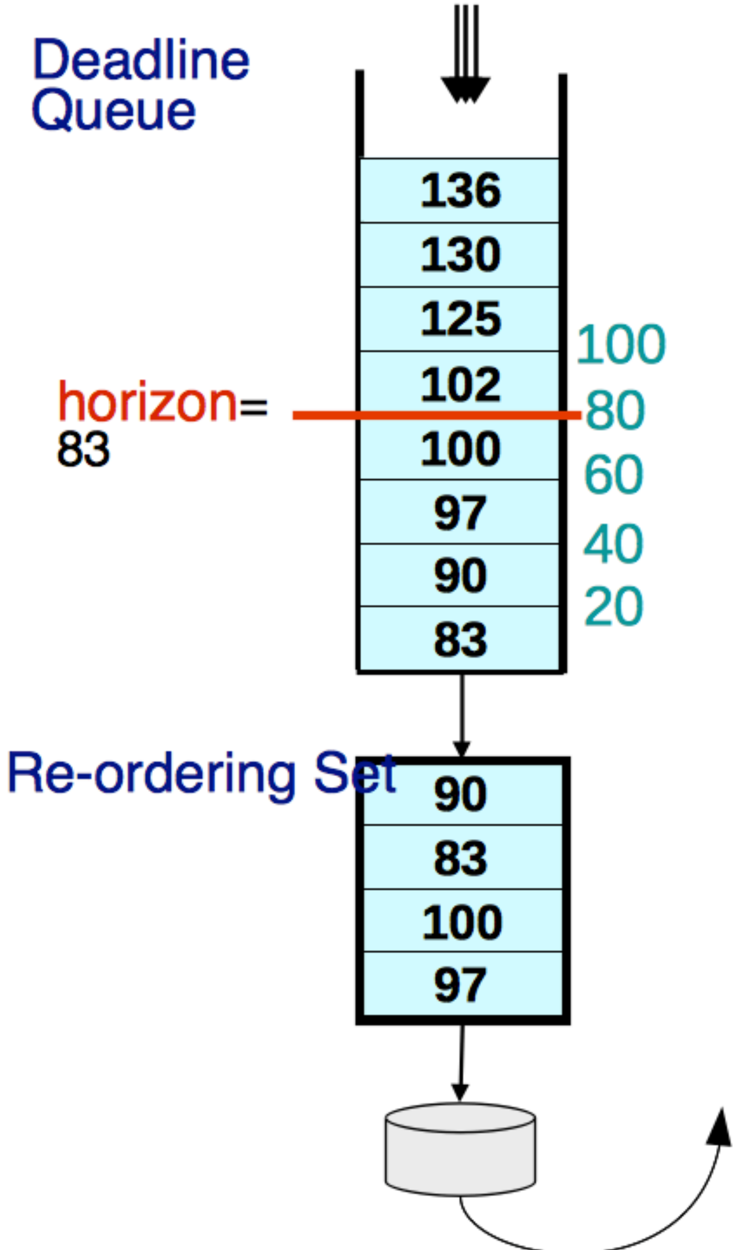
- Workloads specify performance targets
  - Throughput and latency
- Upper layer control mechanism
  - Throughput limiting
  - Deadline assignment based on throughput and latency targets
- Low-level disk schedulers
  - Meet individual request deadlines

Horizon disk scheduling



- Manage I/O in terms of disk time
- Estimate service times based on service time measurements
- Reorder requests within “slack time” before earliest deadline
- Adjust based on optimizations, overload, latency

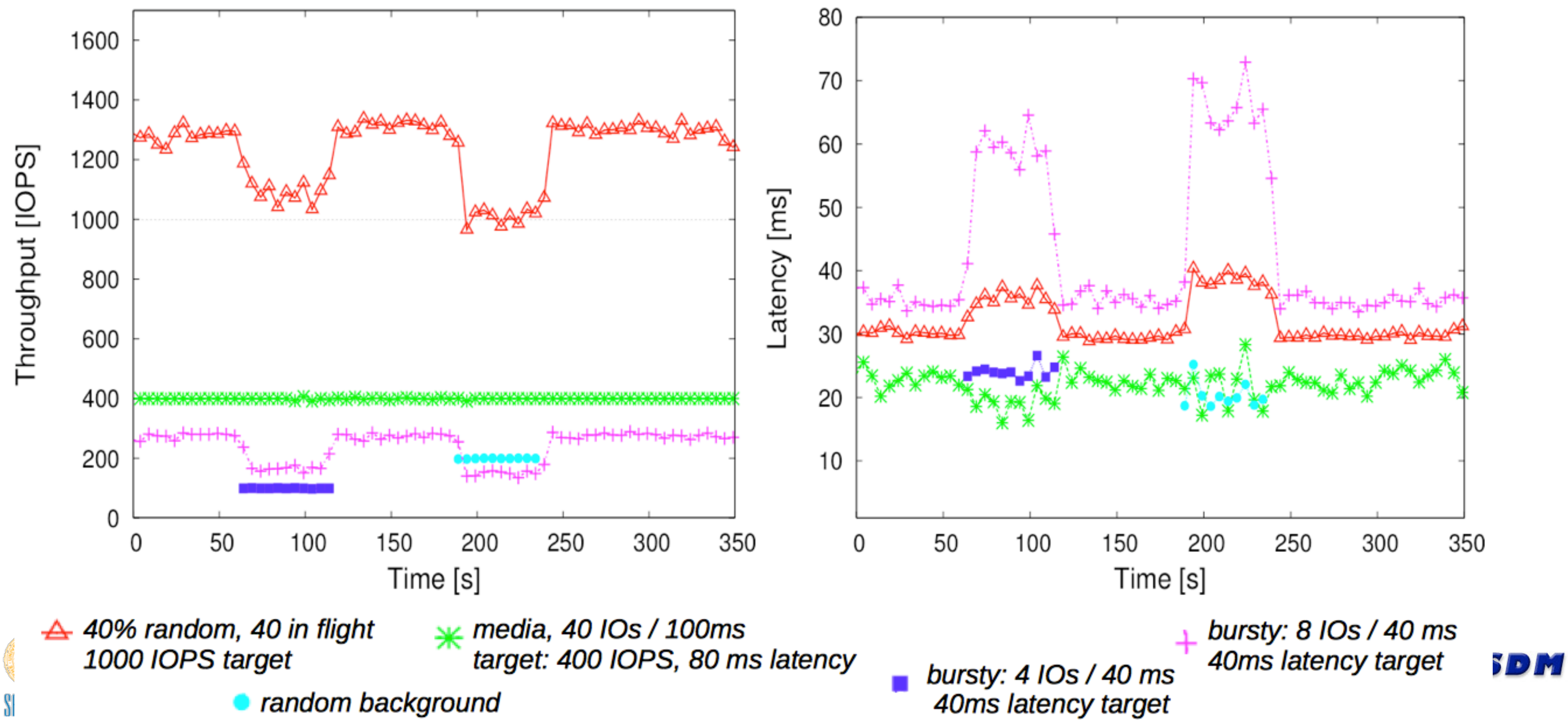
Horizon disk scheduling



- Horizon set to earliest deadline
- Reordering set = everything that will fit before horizon
- Execution times measured as requests complete
- Optimizations
  - Squeeze in more sequential I/Os
  - Use optimistic estimates
  - Increase reordering set (esp. under overload)
  - Increase device queue
    - Larger = better performance
    - Smaller = tighter deadlines

Horizon in use

- Implemented in NetApp's Data ONTAP (data from FAS3040)
- Performance targets associated with volumes
    - Control mechanism at FS entry point
    - Schedulers between RAID and disks



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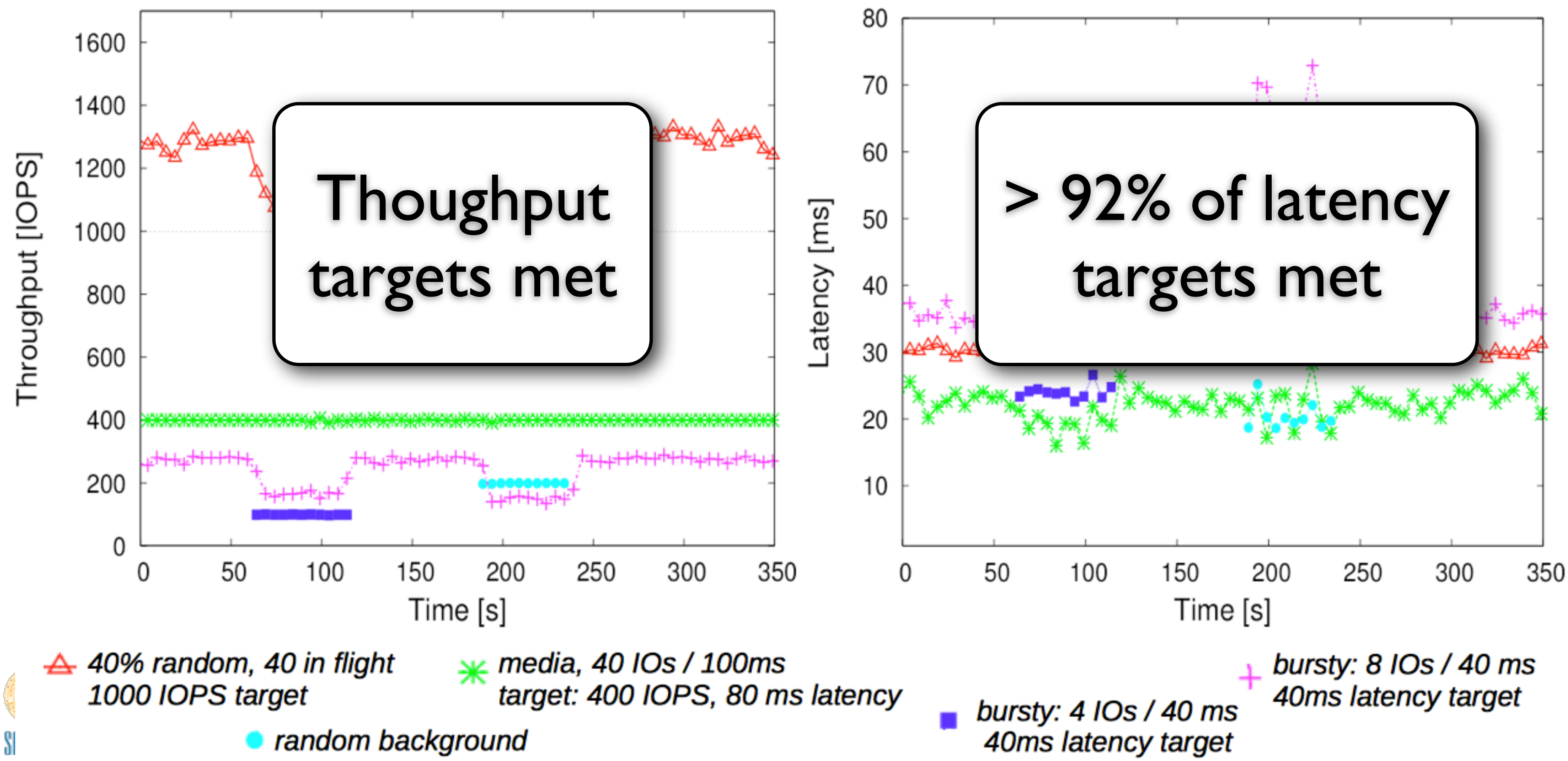

Conclusion

- I/O performance management is needed, challenging, and feasible
  - Many separate elements are involved
  - A unified approach is ideal
- RAD is the basis for a unified solution
  - CPU, disk, network, buffer cache, system
- It is in use in a commercial storage system
- More in the works

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